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# Research of Methodological Principles and Financial Mechanisms of Macro-Strategic Management of the Dynamics of Technological Innovation Systems

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## ABSTRACT

Production and consumption systems need radical innovations to meet the challenges of the post-industrial world. The questions of how systemic innovations or changes in socio-technical systems are implemented and in what form the principles and mechanisms of macro-strategic management of them can be organized are very relevant. Equally relevant is the issue of ensuring the inflow of resources for technological development, such as public funding or private capital. **The aim** of the article is to study a new model for the implementation of innovations in socio-technical systems based on a system dynamics approach. The author applies **methods** of a systematic approach to the analysis of economic processes and phenomena, methods of statistical and econometric analysis, methods of grouping and classification, economic and mathematical modeling, methods of comparative historical and cross-country analysis, forecasting methods and expert judgments. The article examines the methodological principles and mechanisms of macro-strategic management of the dynamics of technological innovation systems and ensuring their financial support. The author proposes a new methodological approach based on system dynamics, which combines two modern concepts of technological innovation systems management: the concept of "innovation engines", based on the research on new technological innovation systems, and the concept of a "three-vector transition module". A model of the emergence or decline of technological innovation systems in the context of various transitional processes (changes) in socio-technical systems is identified. **The scientific novelty** of the research lies in the development of new and improvement of the key methodological approaches currently used for the strategic management of the dynamics of technological innovation systems. **The conclusions** of the article show that the new methodological approach proposed by the author provides an important first step towards the study of more formalized models for studying the dynamics of technological innovation systems.

***Keywords:*** innovation; dynamics; technological innovation system; model; approach; financial support

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## INTRODUCTION

Today, most modern countries are facing serious socio-economic challenges of post-industrial development, such as population aging, climate change, depletion of natural resources, etc. Many studies recognize that gradual changes aimed at increasing production efficiency or introducing new solutions into existing socio-technical systems are insufficient. The authors of these studies increasingly argue that entire systems of production and consumption, which are integral components of socio-technical systems, need radical innovations [1].

The field of science related to the study of the dynamics of technological innovation systems is relatively young. Such studies were initiated by J. Markard [2] in 2008. Questions about how systemic innovations or changes are carried out in socio-technical systems and in what form the principles and mechanisms for managing macro strategic changes in socio-technical systems are implemented remain largely unexplored. An exception is a limited number of studies within the framework of the UN program "Transforming our World: the 2030 Agenda for Sustainable Development".[1]

While this research area has expanded its conceptual base in recent years, two other conceptual strands continue to structure debate and analysis in this area. The first concept of technological innovation systems, i.e. "engines of innovation", was proposed by A. Bergek and M. Hekkert [3]. The second concept of "sustainable transition" was proposed by J. Markard [4]. Numerous empirical studies in the field of retrospective and modern analysis of changes in socio-technical systems and the implementation of systemic innovations have ensured a significant understanding of the patterns and mechanisms that affect the direction and scale of transformational changes. Thus, possible approaches to macro-strategic management of the dynamics of technological innovation systems were discussed in the studies of A. Smith's "Reflexive Management" [5], D. Loorbach "Transition management for sustainable development" [6], R. Kemp. "Strategic niche management" [7]. Currently, the application and development of these analytical approaches and management methods are dominated by qualitative thematic approaches. Although there are notable exceptions, including the work of G. Holtz [8], which explored the use of formal approaches to modeling the transformation of socio-technical systems.

Modeling transitions to sustainable development is a complex task due to the multidimensional processes involved, however, expanding the methodological tools for studying the transition process is a fruitful direction for further study. This poses a challenge for researchers to more accurately formulate and study the cause-and-effect relationships between the various dynamics of developing systems.

This study aims to contribute to this group of scientific research by identifying a model for the emergence or decline of technological innovation systems in the context of various transitional processes (changes) in socio-technical systems and developing a new formal approach on this basis and improvement of already used key methodological approaches to the strategic management of dynamics of technological innovation systems. In many respects, this can be achieved through the use of the concept of A. Bergek and M. Hekkert about "engines of innovation", which is in good agreement with the formal model of system dynamics, both in terms of causation and feedback models. This is also combined with the concept of a "three-vector transition module", developed by the author within the framework of the "sustainable transition" approach.

Thus, this article makes an important contribution to this area of research by proposing a formal model that is a combination of two key approaches. Although the second approach considered in this article, according to such authoritative researchers as J. Markard,

[1] Transforming our World: The 2030 Agenda for Sustainable Development. United Nations. Department of Economic and Social Affairs. Sustainable Development. URL: https://sdgs.un.org/2030agenda (accessed on 18.09.2021).

B. Truffer [2], K. Weber [9], and others, has potential serious advantages, yet, few researchers have considered these aspects in terms of critical analysis.

The main question to which this article is intended to answer is: "How do technological innovation systems arise (or die out) in the conditions of various transient processes in socio-technical systems and what management strategy can increase the efficiency of their dynamics?" This question can be answered by solving the following problems of structural research.

First of all, it is necessary to conduct a deep theoretical and methodological analysis of the existing research on technological innovation systems, the "sustainable transition" approach and other approaches to modeling socio-technical changes.

Next, we present a theoretical description of the modeling approach used in our study.

We then proceed to discuss the results of the behavior of our model based on the analysis of the dynamics of technological innovation systems in the context of the "sustainable transition" approach and under different conditions of resource flows for technological development. Basically, these are external resources, such as public funding or private capital, without which there can be no development of a technological innovation system.

In conclusion, we summarize our findings and prospects for further research.

## THEORETICAL FOUNDATIONS OF MODELING THE DYNAMICS OF TECHNOLOGICAL INNOVATION SYSTEMS

While interest in approaches to modeling the sustainable transition is certainly not ignored in the wider sustainability research community,[2] it is only recently that sustainability advocates have begun in-depth research on the potential of more formal approaches. One of the first pioneering attempts to develop a model explaining the multi-level dynamics of socio-technical changes was undertaken within the framework of the European Union project [10].

The European Union model was based on agent-based modeling techniques with some elements of system dynamics, and an attempt was made to update four previous case studies. The results of this study concluded that the model more closely resembles the analogy of a heuristic method[3] applied to innovation systems, applied in an attempt to capture the overall dynamics of interaction between niches, modes, and landscapes of a technological innovation system. It has proven difficult to model the various vectors in such a way that they represent historical events reflecting the results of previous case studies.

More generally, since 2012, several reviews of the results of case studies on modeling the transition to sustainable development have been published, indicating an emerging thematic research circle [11–13]. The overviews above highlight the importance of downsizing transition models, i.e. focusing the model on specific parts of the overall transition dynamics, in order to improve the performance potential of the model. The need to conduct a sensitivity analysis to test the consequences of "additional assumptions" was also emphasized [14].

A number of researchers argue that evolutionary theory and existing evolutionary models can be a good starting point for the analysis of systemic innovation and socio-technical change, given that transitional models such as "sustainable transition" are already based on evolutionary theory [4]. In addition, J. Halbe [12] concludes that the transition modeling program can be supplemented by combining higher-level abstract approaches such as "sustainable transition" with lower-level abstract approaches to make them more comparable.

We believe that the use of technology innovation systems research is a promising factor

[2] Club of Rome. The Limits to Growth: A Report for the Club of Rome's Projecton the Predicament of Mankind. Universe Books, New York. 1972.

[3] The heuristic method in economics is a method of analyzing economic phenomena and processes based on intuition, analogies, experience, ingenuity, based on the ability to intuitively solve those problems for which a formal mathematical solution is not known.

in the transient modeling agenda. It is noteworthy that, despite their noticeable attractiveness (significance) in the general array of scientific literature on transition processes, as far as we know, there are still no studies that would attempt to model the dynamics of technical and innovative systems. This is paradoxical, given that this approach has already delved into a rather complex understanding of how different processes or functions influence each other and how these interactions shape the emergence of new innovative systems. They provide a good starting point for modeling given that many of the underlying causal relationships and feedback methods have already been detailed and tested in a large number of previous case studies. In this regard, a systematic technological innovation approach contains all the components that fit well into the development of a formal model. At the same time, modeling technological innovation systems can improve our understanding of the complex behavior that results from complex relationships and dynamics. Separate approaches to technological innovation systems have been discussed in detail in other studies [15, 16]. Much of the existing scientific literature on technological innovation systems focuses on understanding how new innovation systems emerge around individual technical innovations such as biogas, solar photovoltaic technologies, or electric vehicles, and on measures to support the development and diffusion of these innovations.

Meanwhile, we recall that the key aspects of the concept of the system of technological innovations are "system functions". Similarly, to the method of A. Bergek and M. Hekkert [3], we distinguish 7 different functions:

1) entrepreneurial activity;
2) knowledge development;
3) knowledge diffusion;
4) search management;
5) market formation;
6) resource mobilization;
7) legitimacy creation.

In addition to these functions, "structural dimensions" are distinguished in the scientific literature. As A. Wieczorek noted in his studies [15], these "structural dimensions" include networks and relations between subjects (for example, at the level of networks or individual contacts), institutions (for example, rules, regulations, customs, procedures, etc.) and technological structures (for example, infrastructure).

Note that there is some confusion in the scientific literature on technological innovation systems about how functions relate to structures. K. Hillman argues that functions should be understood as "processes of building a structure" [14]. From this point of view, functions are processes that form the contours of the development of structures such as new entities, infrastructures, or institutions. Other researchers argue that functions have analytical properties of the innovation system that can be used for evaluation purposes: "functions show the state of a particular innovation system at a certain point in time" [17]. In this article, we largely adhere to the second point of view and assume that the relationship between functions and structures is modeled only at an aggregate level.

Much research on technological innovation systems has been devoted to understanding how the interactions between functions shape the development of these innovations. In this context, as a starting point for developing a model of technological innovation systems, we follow the methodology of R. Suurs [11]. In his study, R. Suurs put forward a hypothesis that functions influence each other at different stages of the development of an innovation system, thereby grouping them into the concept of "innovation engines". More precisely, he developed a configuration of causal relationships based on large-scale case studies. Such a causal analysis agrees with the principle of constructing a formal model of system dynamics since the model contains all the components (for example, causal logic, inhibition, and the feedback method).

R. Suurs [11] identifies four so-called "engines" of innovation. As the first "engine", he considers the "engine of scientific and technological progress", which refers to those models of innovation systems in which the development and diffusion of formal scientific knowledge, supported by government R&D programs, is central. The result of this model of knowledge development and diffusion is the formation of initial pilot projects and other entrepreneurial activities that can increase further financial and institutional support if the results confirm initial expectations, or, conversely, reduce support if the results of these projects are perceived as negative. The key functions of this "engine" are "knowledge development", "knowledge diffusion", "search management" and "resource mobilization".

As the second "engine", R. Suurs considers the "entrepreneurial engine", which refers to models of innovation systems in which the main dynamics of innovation is formed by increasing the number of firms and entrepreneurs active in the innovation system, which increases the legitimacy in the eyes of external investors. In some cases, special lines are also provided for further provision of external resources, for example, to firms seeking temporary financial support to reduce risks when investing in venture capital projects.

Unsustainable commercial activities in niche markets also generate some initial financial resources within the innovation system. These reviews contribute to the development of knowledge through, for example, the publication of feasibility studies or reviews of proposed innovative projects. Consequently, the "learning" dynamic that forms the basis of this "engine" expands from "learning" through seeking to "learning" through action. The key functions of this "engine" are similar to those of the previous "engine of scientific and technological progress", except that "entrepreneurial activity" and "creating legitimacy" play a dominant role here.

The third engine, the "system formation engine", is a model of the dynamics of an innovation system, which is formed through the growing organization of network participants, infrastructure development and institutional reconfiguration. These actors that support the innovation system expand and begin to attract wider public support [11], for example, through the creation of user communities or the institutionalization of market relations through changes in regulations or the construction of additional infrastructure. A practical example here is the creation of a wide network of charging stations for electric vehicles. The "engine of system formation" is a socially and institutionally particularly difficult stage in the development of an innovation system, since the volume of required resources in this model increases significantly compared to the two previous "engines", and the volume of generated internal resources through market sales is still limited. Therefore, from the point of view of functions in this "engine", all functions are important, but the key is the function of "market formation" [17].

The last, fourth, "engine" is the "engine of the market". When the subjects of the innovation system begin to successfully orient themselves in the new institutional configuration created within the framework of the third "engine", it is argued that the innovation system begins to be created by the "market engine". It mainly refers to the innovation system model, which is supported by internal financial resources due to significant market demand, sufficient to provide all the necessary processes in the innovation system. From the point of view of the functional components in this "engine", all functions are important, but the "creating legitimacy" function plays a less important role [17].

In conclusion to the approach of R. Suurs, we note that, despite the presence of clear advantages, this approach has been criticized for a limited conceptual understanding of how the emerging innovation system interacts with its wider environment [17], although, as we note, there are conceptual points of view, for example, as the concept of "creating legitimacy" [13] or the concept of "blocking and stimulating mechanisms" by S. Jacobsson [16]. The interaction between innovation systems and their contexts is important because technological innovation systems do not emerge in a vacuum, and their fate depends on how they interact with the wider environment and what their dynamics are in that environment.

A significant contribution to the formation of a systematic approach to technological innovation was made by A. Bergek [3], who introduced the identification of four types of "contexts" associated with the dynamics of the technological innovation system.

In our model, we integrate the emerging innovation systems with the concept of the "vector of socio-technical transition" [1]. The concepts of "regime" and "landscape", introduced in the context of multi-level analysis, potentially open up fruitful opportunities for studying this interaction between the innovation system and the context [18].

Meanwhile, F. Giles and D. Shot [13] identify four different types of "transition vectors" in their studies, depending on the time of interaction between niche levels, regimes and landscapes within the technological innovation system and the nature of the interaction between the niche and the current socio-technical structure. In turn, according to the time of interaction of levels, they distinguish:

1) the time of the emergence of pressure on the technological landscape, when the niche has not yet received significant development;

2) the time of the emergence of pressure on the technological landscape, when the niche has already developed significantly.

According to the nature of interactions, there are:

1) competitive relations between the niche and the existing regime;

2) co-dependent relationship between the niche and the existing regime.

In their research, F. Geels and J. Schot [13] note that "... niche innovations compete with the existing regime when they seek to replace it. Niche innovations have a codependency relationship if they can be accepted as a competency-enhancing adjunct to the existing regime for solving productivity problems." In our case, we interpret this criterion as follows. In the case of a competitive relationship, the incumbent regime responds to the nascent innovation system by stepping up its lobbying efforts against the nascent technological innovation system and building up innovation efforts in the dominant socio-technical regime, for example, through a new wave of innovation in the existing system of technology. For example, increasing the environmental efficiency of coal technologies in response to innovations in clean technologies. Or when participants choose parts of an emerging innovation system (for example, co-burning of organic waste in coal-fired power plants). The last example entered science as the so-called "sailboat effect", proposed by A. Cooper and C. Smith [17], due to which the efficiency of the current regime increases in the light of the growth of new technological innovation systems. The effect of the "sailboat effect", thus, increases the complexity of the implementation of the innovation system in relation to the current regime. In the case of codependency, this effect is still present, but much more limited, since the emerging innovation system experiences less competition from mainstream markets (simply due to their codependent nature).

All of the above can be summarized in the following three main transitional modules as integrals for emerging technological innovation systems.

1. "Direction of transition", in which:

a) pressure on the landscape occurs at a time when the system of technological innovation has not yet received significant development;

b) the initial resistance to the socio-technical regime is great since the subjects of the regime respond to this pressure by increasing their innovative efforts in the dominant socio-technical regime and only then slowly and hesitantly seek innovation outside the socio-technical regime.

2. "Directions of deregulation and pro-regulation", in which:

a) pressure on the landscape also occurs at a time when the system of technological innovation has not yet received significant development;

b) the subjects of the regime lose faith in the existing socio-technical regime and are actively looking for alternatives, i.e. resistance to the regime is relatively weak.

3. "Strategic path of transformation", which can be divided into two sub-directions:

• "technological substitution direction", in which:

a) pressure on the technological landscape occurs at a time when the technological innovation system has benefited from previous significant support and development efforts;

b) the current actors of the socio-technical regime continue to maintain the existing socio-technical configuration through innovative efforts;

• "direction of reconfiguration", in which:

a) pressure on the landscape also occurs at a time when the system of technological innovation is already well developed;

b) the actors of the socio-technical regime begin to adapt the elements of this innovative system to the existing socio-technical configuration, which implies a relatively low resistance to the regime.

Next, we will explain in detail how we managed to combine these two concepts into a single formal model. Subsequently, we use the model to examine the dynamics of the technological innovation system in the context of the three different transition modules listed above.

## METHODOLOGICAL MECHANISM FOR MODELING THE DYNAMICS OF TECHNOLOGICAL INNOVATION SYSTEMS

Since the rise and fall of a technological innovation system is a dynamically complex phenomenon, it is possible to develop a model using the concept of "system dynamics" that underlies the study of their growth and decline processes. The concept of "system dynamics" allows us to explore a variety of interacting processes and feedbacks, time delays and other non-linear effects. As known, each methodological approach has its advantages and disadvantages, including formal models. First of all, in an attempt to keep the model as aggregated and general as possible, we will present a general model that is not capable of capturing a technology-specific innovation system. In our opinion, this is understandable, given that the systemic approach to technological innovation itself is based on the application of a general concept to study various technological innovations. Secondly, the model assumes a chain connection: "a single technological innovation system" — "a single socio-technical regime". Finally, following the methodology of previous researchers [19, 20] and to improve model performance, we will focus on only one part of the overarching transition dynamics. More precisely, we will aim to replicate the initial growth (and eventual decline) of a technological innovation system in the context of a dominant socio-technical regime (instead of modeling a complete transition from beginning to end). Due to the complexity of the "system dynamics" model, we will restrict ourselves to describing the main postulates (positions) and the results of our study of the dynamics of the model and will not go into a detailed explanation of all equations.

Thus, the main components of "system dynamics" models are stocks, flows and variables. The model recognizes the existence of the four "engines" described above [21], which are sequentially transformed into five "vectors" of feedback. These five cycles consist of seven functions described by A. J. Wieczorek and M. P. Hekkert [15]. In particular, one part represents the development of technology and consists of two feedback "vectors" that balance each other: the "technology creation cycle" and the "knowledge diffusion cycle". Together they form the engine of "scientific and technological development". The other part of the model is mainly related to the development of the market, which consists of three self-reinforcing "vectors" of feedback: the "entrepreneurship engine", the "system formation engine" and the "market engine".

Following the logic of F. Geels and J. Schot [13], we also assume the existence of "regime resistance in relation to the system of technological innovations", i.e. counteracting the self-reinforcing market dynamics of the model.

As for the technological development part of the model, "advanced technological knowledge" and "general technological knowledge" are changed (with a certain delay) as a result of the intervention of external resources (such as public funding or private capital) or after their intervention from internal resources coming from a narrow niche market. Both of these stocks of resources are reduced if their flows are significantly reduced or stopped. Without a steady flow of resources for technological development — as a result of the "resource mobilization" function (a combination of external and internal resources) — there can be no development of a technological innovation system.

In turn, "advanced technological knowledge" and "general technological knowledge" trigger the "search management" function. For example, the successful implementation of a research project that promotes the "development of technological knowledge" and/or the "diffusion of technological knowledge" can lead to inflated expectations, which contributes to the development of the "search management" function [22]. However, we agree with the opinion of A. J. Wieczorek and M. P. Hekkert [15], who believe that "search management [...] is often an interactive and collaborative exchange of ideas between technology producers, technology users and many other participants, in which the technology itself is not a constant, but a variable.

In a number of empirical case studies, "search management" is often a function of government intervention through the implementation of government innovation programs [23]. Consequently, in our model, these trends are reflected in the fact that the function of "search management" is formed not only by the development and diffusion of technologies, but also directly by resources provided from outside (for example, from state innovation programs) and within the country (for example, resources coming from niche markets).

At the same time, it should be emphasized that the key role in the "entrepreneurial motorcycle" is played by the functions "creating the legitimacy of the technological innovation system" and "entrepreneurial activity". The effectiveness of the "creating legitimacy" function depends on both technological and market legitimacy. Technological legitimacy increases as technological knowledge develops and spreads [24]. Market legitimacy increases when the technological innovation system is increasingly institutionalized in relevant categories (such as the development of formal market rules, the creation of intermediary networks, the creation of infrastructure, etc.). In addition, the legitimacy of the market is negatively affected by resistance to the regime (for example, when regime actors try to influence public discourses or lobby to support a system of technological innovations). With regard to the "entrepreneurial driving cycle", we note that a higher level of legitimacy means that entrepreneurs are more likely to operate within a system of technological innovation (not least because this system is perceived as conforming to certain rules and institutions). This leads to a higher level of "entrepreneurial activity". We assume the existence of a curvilinear relationship between the change in the function "creating legitimacy" and the change in the function "entrepreneurial activity". This relationship implies that the higher the legitimacy created, the more entrepreneurs become active, simply because the risk associated with developing such proposals decreases as legitimacy increases, and vice versa [25].

Considering the "system formation engine", we note that here an increase in the "entrepreneurial activity" function leads to a "system formation cycle". More precisely, the strengthening of the "entrepreneurial activity" function involves the development of networks of actors: for example, entrepreneurs organize themselves by expanding networks and creating intermediaries such as industry platforms, user intermediaries and other interest groups. There is also infrastructural activity and attempts at institutional reconfiguration. The model captures this with the stock/flow indicator of these structures.

We assume that the influence of entrepreneurs on the formation of these structures becomes more significant as the "entrepreneurial activity" function grows, which reflects the need to accumulate a certain critical mass before it can have a significant impact. Thus, we once again note the delayed and non-linear relationship between the function of "entrepreneurial activity" and the structures of the system. The emergence of the structures of a technological innovation system provides real value to the emerging links of the system since it implies an expansion of the circle of participants in the support of the innovation system, which leads to wider public support [26]. Thus, the growth of the structures of the technological innovation system increases the legitimacy of the system itself, which makes the "engine cycle of system formation" amplifying in nature [27].

Finally, with regard to the market engine, one can only note that the growth of the "entrepreneurial activity" function also leads (albeit with some delay) to the growth of the "niche market". However, a "niche market" can only truly develop when the actors of the technological innovation system are successfully oriented in creating the structures of the system itself. Moreover, an innovation system can become self-sufficient to provide all the necessary processes in its system, since the "niche market" is able to generate the "total available resource" necessary for this. In this regard, although all "engines" ("vectors") play an important role in creating a technological innovation system, the "market engine vector" is the most powerful self-reinforcing vector, potentially capable of driving the entire system. Finally, we note that, as in the case of the technological link of the model, all functions (stocks) in the "entrepreneurial", "systems", and "market" engines are reduced if resource flows are significantly reduced or stopped.

## EMPIRICAL ANALYSIS

To examine the performance of the model and examine the dynamics of the technological innovation system (growth/stagnation) in the context of different "transition vectors", we applied an experimental model with three variable conditions:

1) landscape time pressure;

2) the type of connection between the technological innovation system and the regime;

3) conditions for the provision of resources.

Under the first condition in our experimental model, the time for landscape pressure to change comes either at the moment when the technological innovation system has already begun to develop due to the provision of external resources or at the moment when it has not yet begun to develop. In the latter case, external resources are provided simultaneously with terrain pressure. This item reflects the first criterion in the typology of "directions of transition" proposed by F.W. Geels and J. Schot [13].

The second variable condition refers to the relationship between the technological innovation system and the regime, which is related to the second criterion proposed by F.W. Geels and J. Schot [13]. Here we observe two different "sailing ship effects" depending on the relationship between the technological innovation system and the regime: one effect occurs when the incumbent regime competes with the technological innovation system, and the other effect occurs when it is interdependent. These "sailing ship effects" differ in effect value (the former is longer) and effect duration (the former is longer). More precisely, we assume that the competitive regime is capable of generating a "sailing ship effect" that increases the "regime resilience to a technological innovation system" by up to 27 percentage points in 205 months; while the codependency regime causes a 5.4 percentage point increase in the "sailing ship effect" over 15 months.

The third variable condition refers to "resource conditions". Resource conditions refer to the availability of external resources (such as finance or human capital) that a technological innovation system can use. As a rule, we assume a fixed volume of resources that does not change between model runs. However, in our experimental model, we distinguish three types of "resource conditions":

a) technologically driven conditions — refers to a situation where there is significant availability of resources for technological development (for example, in the form of public and private support for R&D or a large engineering labor market), but fewer resources for the development market (for example, subsidies for the purchase of environmentally friendly goods);

b) market conditions — refer to the opposite situation, i.e. there are significant resources for market development, but to a lesser extent for technological development;

c) hybrid conditions — refers to a situation where a technological innovation system may initially use heavily technology-oriented resources, and in later stages of development may use significant market-oriented resources.

Finally, we present the results of testing our model using a fixed volume of external resources over both 10 and 15 years to determine the impact of the length of time that resources become available to a technological innovation system over a relatively shorter or longer time period. These time periods are roughly based on an average estimate of the "neutral lag" — the time required between invention and innovation. Thus, we have considered all three transition modules multiplied by three types of resource conditions, running a total of 9 verification tests.

## CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

In this article, we were faced with the task of exploring how technological innovation systems emerge or fade in the context of various socio-technical transition processes and what methodological principles and mechanisms underlie macro strategic management of the dynamics of technological innovation systems. We believe that we have come as close as possible to the goal, mainly with the help of the "system dynamics" model, which is based on the concept of "innovative engines" used in the methodology of new technical and innovative systems, and the concept of the "three-module transition vector" as an integral element of the theory "sustainable transition". Thus, the scientific and methodological contribution of our article is to improve the existing research methodology by integrating two key approaches, namely the system of technological innovation and "sustainable transition", into one holistic model of system dynamics, which can serve as a basis for future research. To illustrate the dynamics resulting from this combination, we developed and applied an experimental model with three state variables characterized by the influence of exogenous conditions. Since, due to the complexity of the "system dynamics" model, in this article, we limited ourselves to describing the main results of our experimental dynamic model and did not go into a detailed description of all equations, we intend to describe them in detail in subsequent publications, already considering the calibration of the model for a specific innovative system.

Thus, our results show that we can be confident in the overall performance of the model, albeit as close to it as possible. In this regard, our proposed new methodological approach provides an important first step towards the study of more formalized models for studying the dynamics of technological innovation systems.

Based on the work presented by us, various directions can be explored. First, in future research, our approach can be adapted to study and improve innovation systems management strategies, for example, by refining based on the conditions for using resources on various transition "vectors". Second, in future research, our approach may be extended to include aspects of the interaction between several technological innovation systems occurring in the context of one or more socio-technical regimes.

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